

# The effects of reflective scattering in the spin correlation parameter in top quark production at the LHC

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## Abstract

The specific effects of the reflective scattering (antishadowing) related to the spin correlations in the top quark production at the LHC are considered. Account for those effects is important in the searches for the signatures of the extra dimensions. It is shown that significant spin correlations could arise at the LHC energies due to reflective scattering and those can affect the signals of the extra dimensions.

# Introduction

The studies of multiparticle production can reveal high degrees of correlations among the spins of produced particles, i.e. particles would be produced with aligned spins. Chou and Yang came to conclusion on existence of such correlations of particle spins on the grounds of their geometrical [1]. Similar conclusion on spin correlations at very high energies has been made later on the base of the reflective scattering mechanism [2]. This mechanism will be discussed later in the context of the top quark production at the LHC.

At the LHC colliding proton beams are not polarized and the only way to perform spin-dependent measurements is to determine the spin directions of final particles via their decay products kinematics. One such possibility to detect global spin correlations [2] is related to  $\Lambda$ -hyperons production and their spins measurements. Another possibility, almost exclusively appropriate to the LHC, is related to the top quark production. This latter process has high statistics and also allows spin measurements through the restoration of the decay products kinematics.

At the LHC, the Standard Model (SM) dominating mechanism of the top quark pairs production is due to gluon fusion. Spin correlations in the top-antitop production in the SM have been calculated in [3]. The main interest in their studies is related to sensitivity of those spin correlations to the presence of the extra dimensions [4].

In present note we briefly report the known results on these correlations and discuss the possible effects due to the reflective scattering mechanism. We estimate the size and sign of these effects for the LHC.

## 1 Spin correlations at the LHC in the Standard Model

As it was noted, in perturbative QCD the top-antitop pairs are produced at the LHC mainly in the gluon fusion processes [3],  $gg \rightarrow t\bar{t}$ , and top decays prior to the hadronization. This feature allows one to determine top quark spin direction by measuring corresponding angles of the decay products. The decay modes in the SM consist of leptonic and hadronic ones:

$$t \rightarrow bW^+ \rightarrow bl^+(l = e, \mu, \tau)\nu_l, bud, bc\bar{s}. \quad (1)$$

The direction of the top quark spin can be reconstructed via its decay products kinematics. The differential decay rates can be written in the top quark rest frame in the form:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}(1 + \kappa_f \cos\theta_f), \quad (2)$$

where  $\Gamma$  is the partial decay width of the particular channel,  $\kappa_f$  is the top-spin analysing power and  $\theta_f$  is the angle between the top-spin axis and direction of momentum of the particle  $f$ . The values of the analysing power for different particles have been calculated in the Standard Model (cf. e.g. [4]). The spin correlation parameter defined as

$$C_{t\bar{t}} = \frac{\sigma(t_{\uparrow}\bar{t}_{\uparrow}) + \sigma(t_{\downarrow}\bar{t}_{\downarrow}) - \sigma(t_{\uparrow}\bar{t}_{\downarrow}) - \sigma(t_{\downarrow}\bar{t}_{\uparrow})}{\sigma(t_{\uparrow}\bar{t}_{\uparrow}) + \sigma(t_{\downarrow}\bar{t}_{\downarrow}) + \sigma(t_{\uparrow}\bar{t}_{\downarrow}) + \sigma(t_{\downarrow}\bar{t}_{\uparrow})} \quad (3)$$

can be extracted from the double differential angular distribution of the respective decay products with angles  $\theta_1$  and  $\theta_2$ :

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = [1 - C_{t\bar{t}} \cos\theta_1 \cos\theta_2]/4. \quad (4)$$

In Eq. (3) the  $\sigma(t_{\alpha}\bar{t}_{\bar{\alpha}})$  are the cross-sections of the top-antitop pair production with respective spin directions. In the SM spin correlation parameter has been calculated for the LHC at the lowest order in  $\alpha_s$  and the values  $C_{t\bar{t}} = 0.30 - 0.31$  have been obtained. The details can be found in [3], it should be noted that numerical values of spin correlations depend on the particular parametrizations of the parton distribution functions. Besides, the value of the top-quark spin correlations can be affected by several mechanisms considered in the next sections.

## 2 Extra dimensiones and the spin correlations

The possibility of the presence extra spacial dimensions in addition to the usual 3+1 dimensional manifold has been considered in [5, 6]. The main purpose for the introduction of the new dimensions was solution of the hierarchy problem, i.e. huge difference in scales of electroweak and gravitational interactions. The 4-dimensional Planck scale  $M_{Pl}$  is connected with the fundamental scale in  $4 + n$  dimensiones  $M$  and radius of the compactified  $n$  extra dimensiones  $R$  by the following relation [5]:

$$M_{Pl} = M(MR)^{n/2}. \quad (5)$$

When the radius  $R$  is large ( $R \sim 0.1$  mm for  $n = 2$ ) the value of  $M$  can be around 1 TeV and it allows one to solve the gauge hierarchy problem. In another theory called 5-dimensional warped geometry theory [6] our space is a five-dimensional anti de Sitter space and the elementary particles except for the graviton are localized on a  $(3 + 1)$ -dimensional brane or branes. We will not discuss the difference in these approaches, it is important to note that in the effective theory graviton propagating in the bulk can be expressed as an infinite tower of Kaluza-Klein (KK)

spin-2 gravitons. Thus, in the 4-dimensional effective theory KK-gravitons interact with the SM fields. These interactions change the total cross-section of the top quark production (increase it by factor 2 for the values of  $M$  around 0.5-1 TeV). It also leads to significant changes in the spin correlation parameter decreasing it from 0.3 in the SM to zero or even negative value in this region of  $M$ . This is due to the spin-2 nature of the KK gravitons. For the other values of  $M$  the role of interactions with KK-gravitons is minimal [4]. There is another global dynamical mechanism which should be taken into consideration. It is related to the reflective scattering.

### 3 Effects of reflective scattering in the spin correlations

The idea that reflective scattering can lead to the global spin correlations of the final particles has been considered in [2]. In this section we apply qualitative conclusions of the above paper to the top-quark production and estimate numerical value of the respective spin correlation parameter. The notion of reflective scattering is related to appearance of the phase factor  $e^{i\pi}$  in the elastic scattering  $2 \rightarrow 2$  matrix element  $S(s, b)$ . We discuss here for simplicity the case of pure imaginary scattering amplitude. The negative sign of  $S(s, b)$  is a manifestation of the fact that the elastic scattering amplitude  $f(s, b)$  is greater than  $1/2$ , note that  $S(s, b) = 1 - 2f(s, b)$ . Reflective scattering is a result of unitarity saturation, when partial amplitude tends to unity at  $s \rightarrow \infty$ . Such saturation realised in the  $U$ -matrix or rational form of the amplitude unitarization at high energies. Thus, as it was noted already, the saturation of unitarity is characterized by the fact that beyond some threshold energy value the elastic scattering matrix element  $S(s, b)$  at  $b = 0$  becomes negative (i.e.  $S(s, b = 0) \rightarrow -1$  at  $s \rightarrow \infty$ ) and the inelastic overlap function

$$\eta(s, b) \equiv \frac{1}{4\pi} \frac{d\sigma_{inel}}{db^2}$$

starts to develop a peripheral impact parameter dependence since

$$\eta(s, b) = f(s, b)(1 - f(s, b)),$$

since  $f > 1/2$ . At the LHC energies this peripheral profile with a maximum at  $b = R(s)$ , where  $R(s)$  is the radius of reflective scattering determined by the relation  $S(s, b = R(s)) = 0$ , should become quite noticeable. The usual exponential (eikonal) form of unitarization does not lead to such a dependence on the impact parameter. The difference in the impact parameter dependencies is illustrated in Fig. 1.

The region around the values of the impact parameter  $b = R(s)$  has the highest probability of the multiparticle production given by the relation  $P_{inel}(s, b) = 4\eta(s, b)$ . Mechanism of reflective scattering leads to suppression of particle production at small impact parameters and the main contribution to the integral multiplicity  $\langle n \rangle(s)$  comes from the region of  $b \sim R(s)$ . Thus, due to peripheral impact parameter dependence of the inelastic overlap function the secondary particles will be mainly produced at the impact parameters  $b \sim R(s)$  and this will lead to imbalance between orbital angular momentum in the initial and final states since the most secondary produced particles would carry large orbital angular momentum. To compensate this imbalance in the orbital momentum the spins of the secondary particles should be correlated, i.e. aligned. Such correlations are expected to appear at the energies where the reflective scattering occurs.

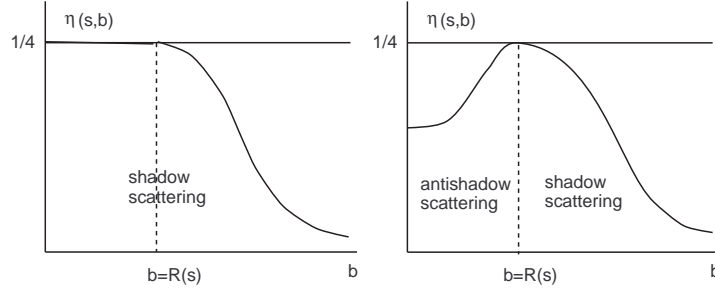


Figure 1: Impact parameter dependence of the inelastic overlap function in the standard unitarization scheme (left panel) and in the unitarization scheme with reflective scattering presence (right panel).

Such considerations are appropriate for all inelastically produced particles, i.e. the spin correlations have a global nature. Despite that, it is difficult to determine spin directions of the most final particles. In this sense, the top quark is one of exclusions (another one is  $\Lambda$ -hyperon productions for example), and as it was already noted, its spin can be directly measured through its decay. On the other side, production of top-quark pairs is an inelastic process and it should be affected by unitarity constraints as well. The imbalance in the orbital momentum will lead to spin correlations in the top-antitop production at the LHC where the reflective scattering should take place.

Thus on the grounds of unitarity saturation, the value of spin correlation parameter  $C_{t\bar{t}}^r$  should be proportional to the relative imbalance of the orbital angular

momentum and to estimate it we make the assumption and just equate these two quantities, i.e.

$$C_{t\bar{t}}^r = -\frac{\Delta L(s)}{L(s)}, \quad (6)$$

where  $L(s)$  is the orbital angular momentum of the initial state in the region of reflective scattering and  $C_{t\bar{t}}^r$  is the spin correlation parameter arising as a result of the reflective scattering. As it was discussed earlier, the spin correlation parameter has the same value for all other particles, but spin of  $t$ -quark can be determined due to its decay. The negative sign in Eq. (6) appears due to the fact that imbalance in orbital angular momentum is compensated by the spin correlations of the final particles in order to provide conservation of the total angular momentum. The numerical value of this spin correlation parameter can be calculated using inelastic overlap function (cf. Fig. 1)

$$C_{t\bar{t}}^r = \frac{\int_0^{R(s)} [1 - P_{inel}(s, b)] b db}{\int_0^{R(s)} b db}. \quad (7)$$

Since  $P_{inel}(s, b) = 4\eta(s, b)$  and  $S^2(s, b) = 1 - 4\eta(s, b)$  we will have the following relation valid in the case when reflective scattering is included (i.e. when saturation of unitarity is assumed at asymptotic energies):

$$C_{t\bar{t}}^r = \frac{2}{R^2(s)} \int_0^{R(s)} S^2(s, b) b db, \quad (8)$$

To obtain the numerical results specific models and parameter values should be used. We apply the model developed in [7]. It is based on the rational form unitarization where  $S(s, b)$  has the form [8]

$$S(s, b) = \frac{1 - U(s, b)}{1 + U(s, b)}. \quad (9)$$

The explicit form of  $U(s, b)$  and values of the model parameters are described e.g. in [9]. The numerical values for the spin correlation parameter can be calculated according to Eq. (8):

$$C_{t\bar{t}}^r \simeq 0.2 (\sqrt{s} = 7 \text{ TeV}) \text{ and } C_{t\bar{t}}^r \simeq 0.4 (\sqrt{s} = 14 \text{ TeV}).$$

Thus, the reflective scattering mechanism at the LHC energies can significantly affect the expected values of the spin correlation parameters, e.g. it can compensate small values of spin correlation parameter predicted due to possible presence of the extra dimensions providing not accounted significant background. There is a way to separate contribution to the spin correlation parameter coming

from SM model gluon-gluon fusion, contribution of the virtual KK-gravitons and reflective scattering. Reflective scattering has a global nature and will lead e.g. to the value  $C_{tt} \simeq 0.2$  at 7 TeV while former processes would provide zero value for this parameter due to independence of the double-parton scattering. Indirectly, this can be tested by measuring  $C_{\Lambda\Lambda}$  for example. It should be noted that spin correlation parameter in the top-antitop production in the helicity basis has already been measured at the LHC by ATLAS [10] (with the value  $0.40^{+0.09}_{-0.08}$ ). This number allows one to make a conclusion on the agreement with the SM predictions. However, one also can speculate on the possibility of the presence of the another mechanism, namely the presence of contribution of the KK-gravitons which is corrected by the reflective scattering effects.

## Conclusion

We discuss here the spin correlation parameter in the top quark production at the LHC. This observable is sensitive to the effects of the extra dimensions and was considered in the literature as a clear signal of the KK-gravitons existence on the brane. At the same time there is an expectation of additional contribution into the spin correlations in top quark production at the LHC energies resulting from the possible existence of the prominent reflective scattering mechanism. This can provide significant background for the detection of the new physics effects associated with the extra dimensions and should be taken into account under the correct interpretations of the experimental results. The effects of reflective scattering can also be verified by the spin correlation parameter measurements in the  $\Lambda$ -hyperon production as it was discussed in [2].

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